Constraints on dark matter-neutrino scattering from the Milky-Way satellites and subhalo modeling for dark acoustic oscillations

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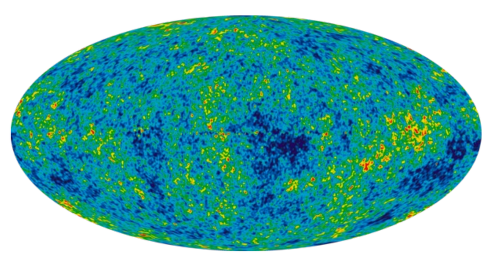
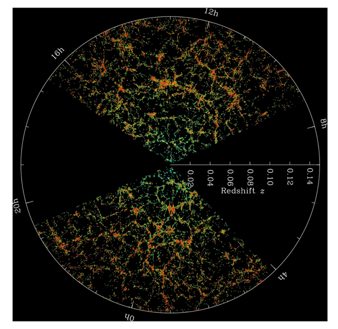
Dark Matter (DM)

DM is gravitationally confirmed by cosmological observations.



https://map.gsfc.nasa.gov/media/121238/index.html



https://www.darkenergysurvey.org/supporting-science/large-scale-structure/

DM properties :
- 27% of the total energy of the universe
- Massive
- Stable

We don't know at (almost) all
- Mass
- Interactions beyond gravity

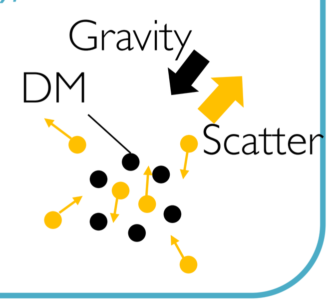
We would like to explore DM property broadly.

Dark acoustic oscillations (DAOs) and the Milky-Way (MW) satellites

DM play an important role in the structure formation.
→ DM is a seed of matter density contrast for galaxy formation.

Dark acoustic oscillations — Neutrinos, photons, baryons (coupled to photons), dark radiation

If DM has interactions with relativistic particles, DM fluctuations are suppressed by their pressure.



DM oscillates between gravity and pressure: DAOs.

Ex) DM-neutrino scattering

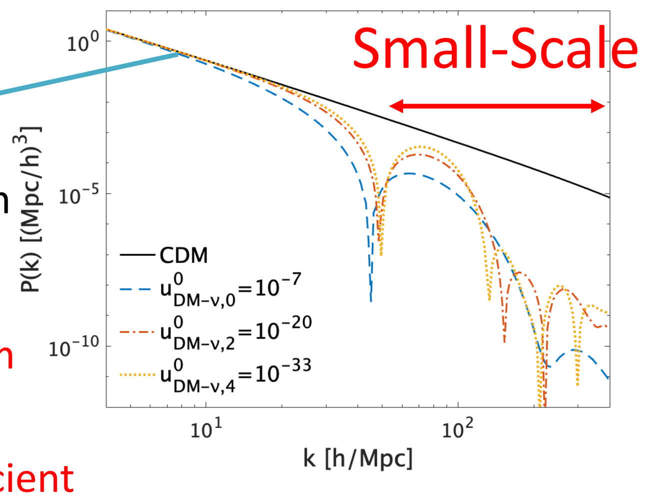
In the linear region,

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} - \Gamma_{{\rm DM}-\nu}(\theta_{\rm DM} - \theta_\nu)$$

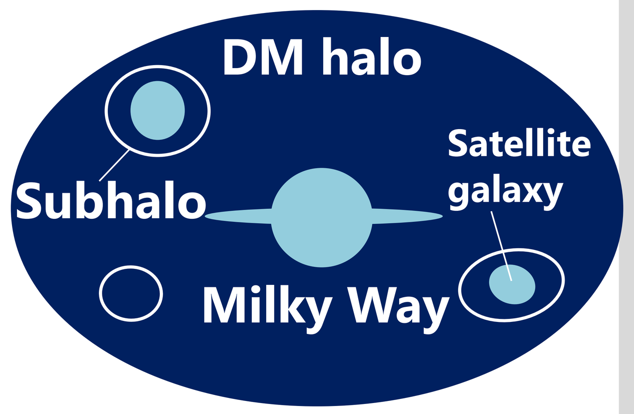
DM velocity divergence — Additional term

$$\Gamma_{{\rm DM}-\nu} \propto \sigma_{{\rm DM}-\nu} n_{\rm DM} \propto \frac{\sigma_{{\rm DM}-\nu}}{m_{\rm DM}}$$ Light DM→efficient

Linear matter power spectrum



Milky-Way satellite galaxies
→Small-scale objects in the universe
→DAOs would reduce the number of the satellite galaxies.



We can test DM scattering from the MW satellites!

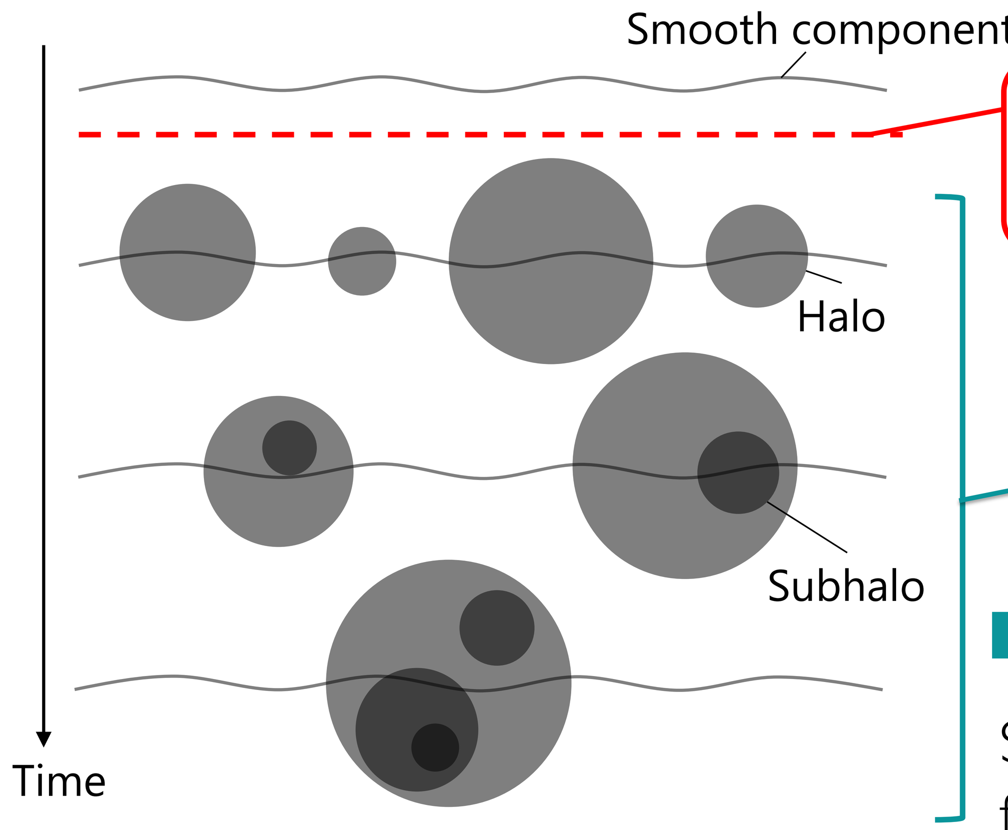
Why the Milky-Way satellites?

- We can test light DM scattering with neutrinos, baryons, photons and dark radiations.
- Even if DM is heavy (GeV-scale), asymmetric DM is not well constrained.
  DM does not annihilate today.
  →Indirect searches by γ-rays would be ineffective.
- Large DM scattering may be achieved in asymmetric DM scenarios.

Why DM-neutrino scattering?

- We may impose relatively strong constraints on DM scattering with the lepton sector.
  Muon, tau rapidly decay→DM could not scatter with mu, tau.
  $U(1)_{L_\mu - L_\tau}$ symmetry→DM-electron interactions would be suppressed.

Subhalo modeling for DAOs



DM decouples with neutrinos in the linear region.

DM gravitationally collapse and then merge, forming halos and subhalos.

→ DM evolution is non-linear.

Semi-analytical model is needed for comprehensive parameter search.

DM collapse to halo:

DM linear fluctuations are spherical:
$$\delta(\boldsymbol{x};R) = \int \delta(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}';R)d^3x',$$
$$W(\boldsymbol{x}-\boldsymbol{x}';R)\begin{cases} <1 & |\boldsymbol{x}-\boldsymbol{x}'| \lesssim R \\ =0 & |\boldsymbol{x}-\boldsymbol{x}'| \gtrsim R \end{cases}$$

We adopt the smooth-k filter:
$$\widetilde{W}^{\rm smooth-k}(kR) = \frac{1}{1+(kR)^\beta} \quad \beta = 3.5$$ [M. Leo, et al. (2018)]

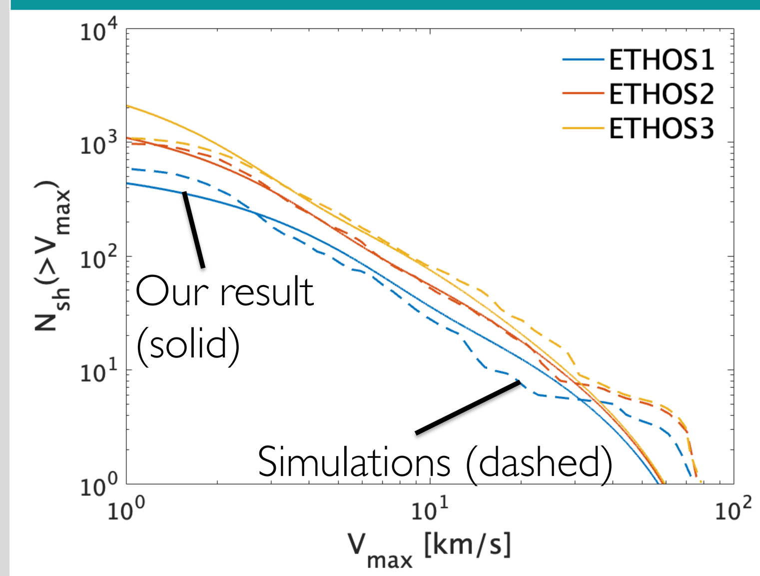
This filter is different from CDM and WDM cases.

DM spherically collapse to halos with $M(\leftrightarrow R)$.

Distributions of halos and subhalos:

Extended Press-Schechter formalism, e.g., subhalo distribution at $z = z_a$
$$\frac{d^2N_{\rm a}}{dm_a dz_a} \propto \frac{1}{\sqrt{2\pi}}\frac{\delta_a - \delta_M}{(s_a - S_M)^{3/2}}\exp\left[-\frac{(\delta_a-\delta_M)^2}{2(s_a - S_M)}\right]$$
m: subhalo mass M: host halo mass

Comparisons with N-body simulations



To confirm our model is variable, we compare publicly available results of N-body simulations with DAOs. [M.Vogelsberger, et al. (2016)]

Our model is very good agreement within a factor of 1.8!

Constraints on DM-neutrino scattering

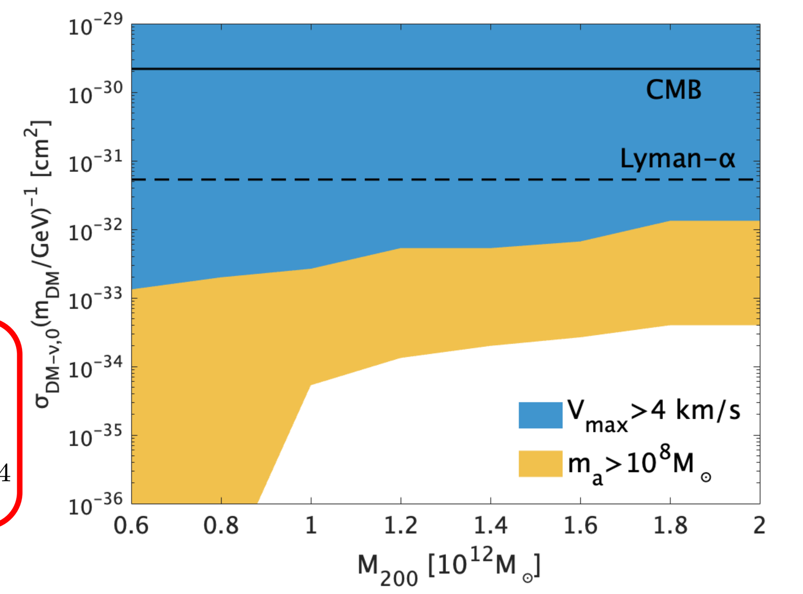
We use the latest data of Milky-Way satellite galaxies from Dark Energy Survey (DES) and PanSTARRS1 (PS1). [DES collaboration (2020)]

We use two data sets:
1. The kinematics data of 94 satellites with $V_{\rm circ} > 4~{\rm km~s^{-1}}$
   →
2. 270 satellites with a satellite forming condition $m_a > 10^8 M_\odot$
   → Subhalo mass at accreation

Constant DM-neutrino cross section

$$\sigma_{{\rm DM}-\nu,0} < 10^{-32}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})$$
$$\sigma_{{\rm DM}-\nu,2} < 10^{-43}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^2$$
$$\sigma_{{\rm DM}-\nu,4} < 10^{-54}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^4$$

$$\sigma_{{\rm DM}-\nu,0} < 4\times10^{-34}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})$$
$$\sigma_{{\rm DM}-\nu,2} < 10^{-46}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^2$$
$$\sigma_{{\rm DM}-\nu,4} < 7\times10^{-59}~{\rm cm^2}~(m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^4$$



$E_\nu^0 \simeq 6.1~{\rm K}$
Cosmic neutrino momentum today — One of uncertainties→Milky-Way halo mass

Summary

- We have developed a semi-analytical subhalo model for DAOs.
- .Our model is very good agreement with N-body simulations including DAOs within a factor of 1.8.
- Using the latest data of Milky-Way satellite galaxies from DES and PS1, we have obtained the most stringent constraints on DM-neutrino scattering.

Reference

K. Akita and S. Ando, JCAP 11 (2023) 037.

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